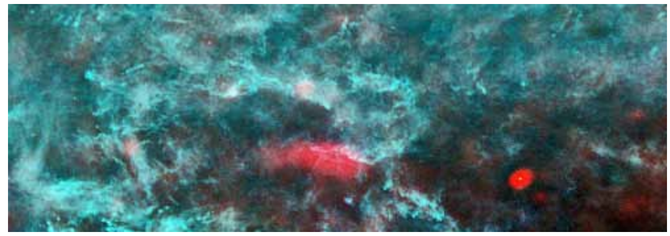
Theoretical Physics

Calculating to capture the Cosmos

by Alexander Stirn



A region in the constellation Perseus imaged by the Planck satellite, which will map the cosmic background radiation with high precision. *Source: ESA*

To understand the cosmic expansion set in train by the Big Bang is the ambitious goal of Viatcheslav Mukhanov, Professor of Theoretical Physics at LMU. He seeks to frame concepts that can explain how the Universe evolved, and illuminate the workings of black holes and dark energy.

To grasp the big picture, one must be careful not to lose sight of the details. Viatcheslav Mukhanov has taken this maxim to heart. Mukhanov, who is Russian but has lived in Munich for 15 years, wants to understand the ultimate "big picture." His goal is to unveil the secrets behind the galaxies and black holes – indeed, the very structure of the Universe. To achieve this end, he knows that he must study the finest details, in the realm of energy quanta and elementary particles, a domain that is inaccessible to all our tools except mathematical ingenuity, and can be described only by formulae.

Viatcheslav Mukhanov is a theoretical quantum cosmologist. At the heart of his work are formulae and complex calculations. With their help, he hopes to explain how the Universe came into being, why it is now expanding at an increasing rate, what part black holes play in all this and what dark energy is made of. He holds a professorship at the Arnold Sommerfeld Center for Theoretical Physics at LMU, and his contributions to his field were recently acknowledged by the award of a *Chaire Blaise Pascal* – the highest honor bestowed on foreign researchers by the French Government.

Mukhanov began to follow in the footsteps of many Nobel Laureates during his studies at the Institute of Physics and Technology in Moscow in the 1970s, where his mentors included Andrei Sakharov and Yakov Zel´dovich. Sakharov, who would later win the Nobel Peace Prize, had been involved in the Soviet effort to develop the hydrogen bomb, while Zel´dovich contributed to the design of the atomic bomb. In the 1970s, these eminent physicists began to make their mark on cosmology. Mukhanov did his doctoral work with another Nobel-winning physicist, Vitaly Ginzburg. His encounter with Ginzburg was crucial for his later career. "I cannot say whom I learned most from, but Ginzburg certainly had a major influence on me," he says.

In the footsteps of Nobel Laureates

The 1970s were an exciting time in cosmology, if also "very speculative," as Mukhanov puts it. Researchers had started to model the first fractions of a second in the existence of the Universe, but they ran into a problem. The conventional concept of the Big Bang and its immediate aftermath was incompatible with the observed structure of the Universe. Instead of the more or less uniform distribution of galaxies we see, the models predicted a much more inhomogeneous structure. In particular, the origin of the large-scale structure of the Universe was a complete mystery. Obviously, something was missing from the recipe.

Mukhanov was still a doctoral student when he identified the missing ingredient. Since Heisenberg's Uncertainty Principle precludes simultaneous determination of the exact position and momentum of a quantum particle, quanta – the tiniest units of any discontinuous physical property – must be subject to a degree of fluctuation. Such fluctuations are predicted to be too minute to leave any trace at the cosmic scale. But Mukhanov proposed that the Universe had undergone a brief early phase of extremely rapid expansion, enlarging by a factor of about 10^{50}. This inflated the fluctuations by the same factor, converting them into density fluctuations. These then seeded the formation of the large-scale structures we now observe.

The rapid phase of expansion was soon dubbed "cosmic inflation," and Mukhanov has continued to pursue the idea throughout his later career. At first, cosmic inflation was just a theoretical construct, a logically motivated model, expressed as a set of mathematical formalisms. Now, 30 years on, the model has been experimentally confirmed. As the Universe continued to expand, the fluctuations were imprinted on the radiation left over from the Big Bang. And this message from the remotest past can still be read in the cosmic microwave background, the weak (long-wavelength) radiation that pervades the Universe. "In principle," says Mukhanov, "this radiation provides us with a photograph of the early Universe." Measurements of the intensity fluctuations in the background radiation agree to 99.9 % with the predictions he made in 1981. In a few months, the latest data from the European Planck satellite will become available. The map that emerges from the Planck Mission will be 500 times more precise than the previous version, and promises to increase the level of agreement with Mukhanov's theory still further.

Trying to understand the expansion of the Universe

"Physical theory cannot remain abstract; it must describe what's out there," Mukhanov says. That is why it is important that theories should be testable. "Not every theoretician gets such a chance but, of course, when the predictions agree with the experimental values – as with the quantum fluctuations – it is enormously satisfying." But not all the riddles associated with inflation have been resolved. For instance, Mukhanov's theory makes use of a hypothetical elementary particle whose existence can never be demonstrated, even with the most powerful accelerators. "A detailed picture of the inflationary phase is still lacking. But such a picture is not a prerequisite for testable predictions. All we need for them is a well-motivated and efficient theory."

Nevertheless, Mukhanov continues to work on his theory. For him, it is a matter of professional self-respect. In recent years he has introduced two further modifications, which he calls K inflation and vector inflation respectively. The new models make a number of further assumptions, such as the idea that, prior to the onset of inflation, the pattern of quanta in the young Universe was dominated by so-called vector fields – spatial structures that are oriented in different directions. On a large scale such vector fields will tend to cancel out, thus giving rise to a homogeneous Universe. On the other hand, each individual vector field can itself generate perturbations comparable to those produced by quantum fluctuations, which could also serve as the germs of stars and galaxies. However, Mukhanov readily admits that "at the moment, this theory is not much more convincing than the older models."

Quite apart from its role in the immediate aftermath of the Big Bang, the expansion of the Universe continues to fascinate Mukhanov. For, as we now know, the rate of expansion later began to accelerate again. Most researchers think that a mysterious force called dark energy is responsible for this. Dark energy is a theoretical construct that affects structure-forming processes in the Universe, but its source remains unclear. "Dark energy sounds like magic and, indeed, that's what it is. All we can say about it is that it dominates the entire Universe," says Mukhanov. Furthermore, if dark energy is to drive the accelerated expansion, it must act, unlike normal energy, in opposition to gravity.

"It is not at all clear why we are currently in a second phase of accelerated expansion; it is a real mystery," says Mukhanov. Naturally, there are theories, including one he has developed in collaboration with colleagues. This invokes something called K essence, a form of kinetic energy that appears to flout the conventional laws of physics but can account for the strange motions observed in the Universe. "I would not describe the models as beautiful, but they give us some ideas as to how to proceed."

Making predictions about the properties of dark energy

If a theory is to make a real contribution to progress, it must make predictions that can be tested experimentally. Perhaps surprisingly, even the current models of cosmic expansion allow one to make predictions about the properties of dark energy. The rates of cosmic acceleration due to dark energy vary depending on the factors cosmologists plug into these theories. "However, our present methods of measurement are not precise enough to allow us to confirm or reject any of the competing models," says Mukhanov. "And anyway, at this stage just playing around with ideas is no bad thing."

For a cosmologist like Mukhanov, ideas are what counts; they are the driving force of all advances in science. "In theoretical physics, one cannot plan for the future; one must wait and see how things pan out," he comments. "If I get a good idea tomorrow, everything can change." Hard work is the basic requirement; one must keep abreast of developments at all times. But it alone is no guarantee of success; on its own, it cannot generate good ideas. That needs more, exchanges with colleagues, inspiration and, above all – curiosity.

That is why Viatcheslav Mukhanov has high hopes for his term as the holder of a *Chaire Blaise Pascal*. In March he will move to Paris for a year as a visiting researcher, with financial support from the French Government and the Île-de-France region. During his stay in France, he plans to spend time at the École normale supérieure, the Collège de France, and the Institut d'Astrophysique. He looks forward to collaborating with cosmologists, string theorists and particle physicists, to presenting talks and to giving his imagination free rein. "The exchange of ideas is the most important thing and, who knows, maybe some interesting projects will come out of it all."

And they don't all have to deal with inflation. One of Mukhanov's latest ideas concerns black holes. Researchers long thought that absolutely nothing can ever escape from their omnivorous maws. However, the well-known British physicist Stephen Hawking has challenged this view by suggesting that even black holes can emit radiation, albeit in minuscule amounts, as a result of quantum fluctuations on their surfaces. According to his calculations, the energy of this radiation should be distributed continuously over a large portion of the electromagnetic spectrum, just like that of the classical black-body (the physicist's term for an ideal source of heat radiation) which led Max Planck to the quantum concept and to his famous constant.

Viatcheslav Mukhanov is not persuaded by Hawking's model. His own calculations point in a different direction. Planck's basic insight was that everything in nature is quantized and divisible into discrete and fundamental units. One of these units is the so-called Planck surface, which corresponds to an area of 10-66 cm^2. If the surface area, or event horizon, of a black hole must consist of an integral number of these units, then Hawking's thesis would not hold. Instead of the continuous spectrum characteristic of black-body radiation, the black hole would emit energy in the form of spectral lines. And since the behavior of a black hole is dominated by the laws of quantum physics, Mukhanov believes that its surface is most likely to be so too. Unfortunately, like Hawking's prediction, Mukhanov's idea is not amenable to experimental test. Indeed, if such a test were available and had verified Hawking's model, it would probably have earned its inventor a Nobel Prize.

Apropos prizes … In 1988 Viatcheslav Mukhanov received the Gold Medal for Outstanding Achievement awarded by the Russian Academy of Sciences. In 2006 the Oskar Klein Medal was conferred on him by Stockholm University and the Nobel Prize Committee. In 2009 he was honored by the Thomalla Foundation in Switzerland. And at the end of last year, the *Chaire Blaise Pascal* joined the list of his accolades. Nobel Prizes in his field have, however, gone to other cosmologists in recent years. In 2006, the Physics Prize was given to George Smoot and John Mather for their measurements of the fluctuations in the cosmic microwave background, which agreed with Mukhanov's predictions. Last year, three Americans won the Prize for their discovery of the acceleration of cosmic expansion due to dark energy.

Is there still room for Viatcheslav Mukhanov? The question elicits a quiet smile, and a response that is perhaps typical for a theoretical physicist: "We'll see; at any rate, the chances are greater than zero."

Prof. Dr. Viatcheslav Mukhanov has held the Chair of Cosmology at LMU since 1997. Born in 1956, Mukhanov studied at the Institute of Physics and Technology in Moscow, where his doctoral supervisor was Vitaly Ginzburg. He went on to work at the Institute for Nuclear Research and at the Lebedev Institute of the Russian Academy of Sciences, before moving to the ETH in Zurich in 1992. In late 2011, he was awarded a *Chaire Blaise Pascal*.

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